Vertical Ozone Profiles in the Uinta Basin and Validating Drones as an Air Measurement Platform

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Executive Summary

In situ ozone measurements were made resulting in vertical profiles using two flight platforms (rotary wing drones and high altitude balloons) and two sensor systems (ozonesondes and AtmoSniffers). Computational Fluid Dynamics (CFD) calculations were completed for heavy lift rotary wing drones and compared to actual measurements in the open air. Measurements were made in the Uinta Basin and on the Wasatch Front.

The primary conclusions are:

1. Drones are a useful platform for vertical air measurement during ascent but not for descent. The air intake position of the sensor does not appear to matter as long as the drone is stationary or ascending.
2. CFD calculations are very useful for predicting airflow around sensors in a dynamic environment such as the downwash of a drone's rotor disk.
3. Drones are easier to deploy than balloon systems, have a more controlled flight path, and provide excellent agreement with balloon borne sondes.
4. Drones can only be used near ground level but can be safely operated near cell phone towers, radio antenna towers, or similar obstructions to allow for a higher altitude vertical air profile while still remaining in compliance with FAA Part 107 regulations.
5. The evolution of ozone in the mornings starts at higher altitudes above ground level and progresses downward. Ozone becomes uniform in altitude during the middle of the day. The evening mix-out of ozone is random in altitude.

High altitude balloons were used for measurements from ground level to the mid-stratosphere carrying an industry standard ozonesonde. The balloons also carried AtmoSniffers, an air sensor payload being developed in-house. In addition, rotary-wing drones were flown with similar air sensor payloads. This project had four primary goals: (1) Study upper-level transport of ozone above the Uinta Basin, (2) Determine the flight characteristics and air flow dynamics of drones used for air quality measurements, (3) Validate the drone measurements against the balloon borne measurements, (4) Determine if drones with lightweight air sensor payloads can reliably measure air pollution vertical profiles in the lower atmosphere.

COVID travel restrictions made completion of the first goal impossible. Travel and group work restrictions were lifted on June 25, 2021. Tropospheric intrusions of stratospheric ozone are known to happen in spring, not summer. This also compressed the time available for flights on the Wasatch Front resulting in a reduced number of flights. While we obtained significantly less data than we wanted, those data sets are in excellent agreement with both calculations and earlier data sets. Goals 2, 3, and 4 were accomplished.

Background and Significance

Balloon-borne ozonesondes are considered the gold standard in ozone measurements and have been in use since 1934[1,2]. However, not only are balloons personnel- and time- intensive, they are also at the mercy of wind conditions. On the other hand, a drone platform is easily maneuverable and can target predetermined air columns in a matter of minutes using only two operators. Although drones are limited in altitude by FAA regulations, waivers can easily be applied for. Alternatively, flights can be conducted near established obstacles such as cell phone or radio towers. Operations for this project were completed 40-70 meters from a 47-meter tall cell phone tower. This location was selected because it is 2.43 km from a UDAQ air measurement station that was used to establish measurement baselines. Drone flights were conducted both in tandem with - and independently - of the balloon flights. The drone carried sensor payloads close to the balloon flight path at launch and at landing. A unique feature of our work is the use of drones and **computational fluid dynamics** (CFD) simulations to (1) quantify uncertainty in drone sensor measurements, and (2) correct drone measurement in light of said uncertainty.

Findings from this work will help our understanding of air exchange processes and pollutants mass transport and validate drones as a measurement platform for that task.

This work is collaborative between the University of Utah and Weber State University. This project leveraged existing equipment (drones, sensors, computational nodes, etc…), simulation software (the Wasatch open-source code), and ongoing work being conducted by both PIs.

Objectives

(1) Upper-level transport of ozone above the Uinta Basin

This objective aims at studying the vertical transport of ozone from the stratosphere to the ground. Measurements elsewhere have shown that as much as 13% of ground level ozone can be the result of downward transport from the stratosphere[3,4]. Studies have shown this to occur primarily in the spring which is consistent with previous years' measurements made by the Weber State University HARBOR team in the Uinta Basin.

COVID restrictions on travel, fieldwork, and group meetings were lifted June 25, 2021, well into summer weather patterns. Thus, focused measurements for this objective were not possible.

We are nonetheless able to make some conclusions based on earlier observations and the published literature and those conclusions are reported below.

(2) Flight characteristics and air flow dynamics of drones used for air quality measurements

Two drones were used for testing purposes, a DJI brand Matrice 600 Pro heavy lift drone (6.0 kg max payload) and a much smaller DJI Flame Wheel F550 hexacopter drone (1.2 kg max payload) (see Fig. 1). Both drones carried their payloads safely and had stable flight. Landing gear configuration turns out to be critical, as detailed below in the Results section. Measurements and computer simulations for air flow were performed on the large M600 Pro drone. The conclusions apply to other rotary wing drones.

(a) DJI Matrice 600 **(a) DJI Flame Wheel F550**

Figure 1: Two drones used for vertical measurements in our study. Images are from the manufacturer website[5,6].

Air flow was measured with a small anemometer and was videoed with a light ribbon (sailing tell-tail) used as a probe. Air sensor systems (a standard NOAA approved ozonesonde and an in-house designed sensor system called the AtmoSniffer) were installed on the M600 Pro drone in various configurations and with different air intake tube designs. The drone was flown a few meters from a calibrated ozonesonde suspended on a pole.

Computational Fluid Dynamics calculations were conducted with the in-house CFD simulation code, Wasatch, our locally developed, open-source CFD code. The goal of our CFD simulations was to evaluate the air flow and ozone transport under and around the drone during ascent and descent and investigate the effects of the rotors on ozone measurements. A computational model for the drone rotors was implemented to model the air flow created by the drone. A time-dependent boundary condition for scalar transport was implemented to perform simulations with vertical gradients of ozone.

(3) Drone measurements compared to balloon borne measurements

A Matrice 600 Pro heavy lift drone was compared to a standard weather balloon system. The lift capacity of the M600 is 6.0 kg which is comparable to the total allowed payload of a standard weather balloon of 5.4 kg which is the FAA limit for flight without special waivers.

For this objective the drone was outfitted with the same MetOne ozonesonde as the balloon. The drone was launched close to the balloon to the FAA limit of 400 feet AGL. We arrived at the landing of the balloon within minutes of touchdown and immediately flew the drone borne ozonesonde over approximately the same path as the balloon for the final 400 feet of flight. The results were indistinguishable.

(4) Determine if drones with lightweight air sensors payloads can reliably measure air pollution vertical profiles in the lower atmosphere

In addition to the flights paralleling the weather balloon (objective 3) we also performed multiple flights near a statically suspended ozonesonde at a location 2.44 km from a UDAQ air monitoring station (Harrisville). Two dawn-to-dusk sets of nearly continuous flights were conducted to compare with similar moored balloon (aerostat) flights. The results were positive.

Our CFD simulations also contributed to this objective by providing insight into the ozone transport and mixing around the drone during flights. The trends observed in our simulations were in good agreement with experimental results and allowed us to identify an optimal flight pattern and intake tube location.

Methods

Objective 1: Ozone Transport in the Uinta Basin.

The original plan was to do a series of balloon flights from ground level to approximately 15 mb (28 km). These were to run from April 2021 to early June 2021, a period of time when ozone vertical transport is suspected to occur. A balloon payload including an ozonesonde/radiosonde and an AtmoSniffer (which contains two ozone sensors) were to be flown. Because of COVID travel restrictions this field work was impossible to complete.

We were able to complete two flights in July 2021. The first flight was flawless, but the second flight lost data telemetry after 7.1 km ASL. (Inspection upon landing showed that inflight turbulence tore the radiosonde off of the ozonesonde.)

Review of ozonesonde data from flights made in previous years does show strong indications of ozone transport from the stratosphere towards the troposphere.

Objective 2: Flight characteristics and air flow dynamics of drones used for air quality measurements.

Two drones (one large and one “small”) were loaded with air sensing payloads and flown near a calibrated ozonesonde suspended above the ground. The large drone was also flown to an altitude of 550 feet AGL (we were operating next to a 154 foot tall cell phone tower). (Using imperial units to be consistent with FAA regulations.) These tests allowed us to compare to a known ozone level and test for RF interference.

Video was taken of a sailboat “tell-tale” (small ribbon) attached to a long slender pole. The ribbon was used to map out actual air flow patterns. We also measured air flow velocity with a portable anemometer placed in known positions under and above the drone.

During these experiments the drone was hovering approximately 1.5 rotor disk diameters above the ground. This altitude was chosen to be within reach of the ground teams and also above the distance at which “ground effect” in helicopters is commonly experienced. (Ground effect is usually assumed to occur at altitudes below approximately ½ the rotor disk diameter. We were operating above uneven ground on purpose to further reduce any ground effect issues. Ground effect is when air rebounding off of the ground changes the flight characteristics of the aircraft.)

These measurements were compared to detailed computational fluid dynamics calculations using the Wasatch CFD code[7]. Our objective is to develop a computational model to simulate the airflow generated by a drone. In general, to simulate these types of flows, complex boundary conditions are generally specified in the interior of the computational domain at the rotor sites including moving boundaries to represent the motion of the rotor blades and the ensuing vortical structures produced by the motion of the blades[8,9]. Because capturing such details will have a secondary effect on the bulk airflow motion and its impact on sensor measurements, we argue that a simpler model for the rotors can be used. By considering the overall momentum produced by a rotor, a momentum source term can be added to the fluid flow equations. Numerically, this source converges rapidly to the desired momentum specification, but also produces spatial fluctuations that mimic the turbulent nature of actual rotors. In addition to the rotors, we also represent the body and arms of the drone as well as the payload as solid intrusions.

Objective 3: Drone measurements compared to balloon borne measurements.

Our ability to obtain these measurements was severely limited by COVID travel restrictions. We were able to obtain three data sets from two balloon flights, two during ascent and one during descent.

The drone and balloon were outfitted with identical ozonesonde/radiosonde systems. The drone pilot attempted to match the flight profile of the balloon but about 20 meters to the side. Using the balloon as a known “obstruction” (for which FAA NOTAMs had been filed) we flew the drone to an altitude of approximately 550 feet then immediately returned to the launch point.

We reached the landing point of the balloon payload (under parachute) a few minutes after it landed. We deployed the drone over the nearly same flight path as the balloon for the bottom 400 vertical feet of flight.

As the second flight lost telemetry, there was no reason to fly the drone for the landing portion of that balloon flight.

One limitation is the speed of ascent. The balloon rises at approximately 5.5 m/s but the drone's maximum ascent is 5.0 m/s. While this difference is small it was clear that the balloon was quickly outpacing the drone.

Objective 4: Determine if drones with lightweight air sensor payloads can reliably measure air pollution vertical profiles in the lower atmosphere.

Data collected as part of objectives 2 and 3 were used as part of this objective.

Two drones were used for testing purposes, a DJI brand Matrice 600 Pro heavy lift drone (6.0 kg max payload) and a much smaller DJI Flame Wheel F550 hexacopter drone (1.2 kg max payload). Various mounting configurations were tested for three different air sensors.

We also flew past a suspended ozonesonde in four different flight modes: hovering, ascending, descending, and sideways. The sideways flights were at the same altitude as the suspended sensor and included approaches, receding, and flybys.

Air intake tubes were tested at different positions both inside and outside the rotor wash. We also mounted an air sensor on top of the large drone.

The landing gear (legs) on the small drone could not accommodate the larger sized payloads such as the ozonesonde. The small drone was able to lift and fly the ozonesonde, but could not safely land with it.

Computational fluid dynamics calculations were performed for hovering, ascent, and descent in an attempt to explain a commonly observed discrepancy when measuring against a background vertical gradient concentration. Perhaps this is the most important discovery of this work which provides a rational explanation for the differences in measurement observed during ascent and descent.

Results and Implications

Our primary conclusion is that ***drones are an effective platform for measuring air quality when guidelines for sensor placement are followed***. In addition, we list the following results and implications.

1. The computational fluid dynamics calculations and the measured data are in excellent agreement and have the following two major findings:
    a. Measurement on ascent or while hovering is good, measurement on descent is not recommended. On descent it is difficult to know where the air being measured is coming from (from above or from well below the drone).

b. Location of the air intake does not seem to matter. The air immediately above the drone is “quiet” and is drawn into the rotor wash. The air directly in the center of the drone experiences significant upward flow but primarily contains air from above the drone. There is some issue with air flow across the opening causing a drop in pressure at the air intake tube. We recommend directing the tube opening directly upward or downward to avoid any issues with a possible Venturi effect.

2. Drones are significantly easier to deploy than free flying balloons or tethered aerostats. A small flight field without structures or personnel below is all that is needed. We found that a small flight operations area that is 50 meters by 50 meters is sufficient for safe operations even with very large drones (the Matrice 600 Pro is nearly two meters across and stands 1.5 meters high).
3. Drones are superior to moored balloons or aerostats in both low and moderate winds. Operational max wind speed will depend on the particular drone and payload combination but operation in winds between 20 and 30 MPH is common (9 to 13 m/s). Our experience with aerostats is that wind speeds above 10 MPH (4.5 m/s) are very difficult to work in and the aerostat will have a significant horizontal offset that puts heavy constraints on the flight field. Free flying balloons are completely at the mercy of the winds and you have no control over the location of the air measurements.
4. Controlled flight with drones is significantly easier than with free flying or moored balloons. The measurement time for most air sensors ranges from a few seconds to over a minute. Free flying balloons rise faster than the measurement time. We were able to control the ascent of the drone very precisely.
5. Drones require fewer personnel for flight operations and do not require extensive recovery efforts as compared to high altitude balloons.
6. High altitude free flying balloons are superior for collecting vertical profiles of the entire troposphere up to the mid-stratosphere.
7. Drone altitude measurements are limited by FAA altitude restrictions. These are easy to work with by selecting a flight operations area close to known obstructions such as tall antennas or cell phone towers. We found no interference problems with flight control when operating very close (less than 30 meters) to cell phone towers or from nearby radio broadcasting antennas. Most modern drones will automatically “Return to Home” if they lose signal and fly with GPS to the home point and land. Antennas, water towers, etc. are commonly 200 to 300 feet high which allow for drone flights as high as 700 feet AGL. Our personal experience is that flights higher than 600 feet should only be attempted

by very experienced drone pilots. (Note: non-recreational flying requires an FAA part 107 remote pilot's license.)

8. The work has been presented at the AICHE annual meeting[10].
9. A manuscript is currently being prepared for submission to a peer-reviewed journal.

Objective 1: Ozone Transport in the Uinta Basin.

As stated previously, due to COVID related travel restrictions, we were unable to complete this objective. We were able to complete one successful balloon flight in July of 2021 and the data obtained from that is presented in figure 2. This data was also used for objective 3. The trend observed in figure 2 is as expected with increasing ozone concentration as the balloon ascends through the troposphere and into the stratosphere. There was no significant tropospheric intrusion given that the flight took place in mid-summer past the season those events normally occur.

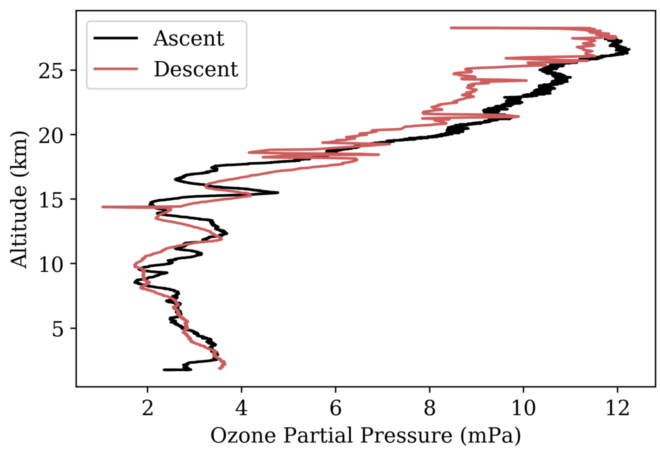


Figure 2: Ozone levels obtained from an ozonesonde tethered below a high altitude balloon launched on July 1, 2021.

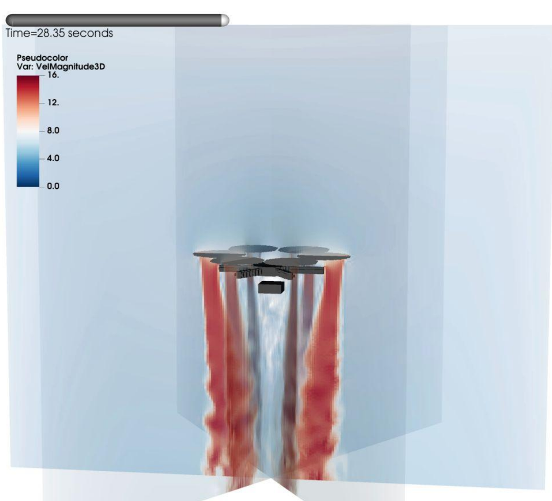
Objective 2: Flight characteristics and air flow dynamics of drones used for air quality measurements.[1]

We used an anemometer to estimate the air velocity about 1 meter underneath the larger drone (DJI M600). Our measurements suggest that the maximum downward (vertical) component of the velocity directly underneath the rotors is approximately 10 m/s. When the anemometer was moved toward the center of the drone, the velocity decreased rapidly to around 1 m/s or less. We also placed a light ribbon attached to a

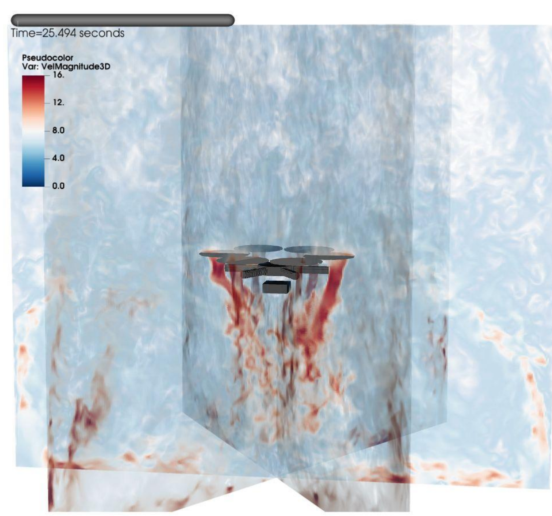
[1]Both drones carried their payloads safely and had stable flight. The smaller drone crashed due to a flight controller (DJI A2) system failure unrelated to the air sensor payload. The main problem with the small drone was landing with a large payload that exceeded the size of the landing gear legs. Neither drone had any indication of flight interference due to nearby radio frequency sources.

pole at various locations underneath the drone to estimate flow direction. Underneath the center of the drone, the probe pointed upwards meaning some air was flowing upwards toward the drone opposite the flow direction from the rotors. This indicates that some air is recirculating in that region.

Our simulations use a model for the drone rotors that adds a momentum source term to the governing equations based on the force needed to balance the weight of the drone and payload. Figure 3 shows the three dimensional computational domain with slices through each of the rotors to show the air flow. In our simulations of hover and ascent, the vertical component of the air velocity below the rotors was around 10 m/s which is in agreement with the anemometer readings. The air flow under the center of the drone was also in agreement with the anemometer readings. Figure 4 shows a 2D slice of the air flow with velocity vectors of the drone during ascent and descent. The velocity vectors indicate that for ascent and hover (not shown) there is predominantly flow downward. However, underneath the center of the drone, the velocity vectors show some flow upwards towards the payload which is in agreement with the probe measurements. The velocity vectors also show that fresh air is flowing into the region around the ozonesonde from above the drone. This ensures that the ozonesonde is not measuring stagnant air. Our simulations indicate that the residence time of air underneath the drone is around 1-2 seconds. Our results are consistent with other studies[11,12].



(a)



(b)

Figure 3: 3D simulations air flow from the DJI M600 during (a) ascent and (b) descent showing the critical difference in airflow structures created by the drone. These flow dynamics will affect the entrainment of particles and gases into the sensor. Animations from these simulations can be found here: https://tinyurl.com/2asdz989.

Comparing the simulations from ascent and descent, it is clear from both figures 3 and 4 that the drone has a much greater influence on the surrounding air during descent. When the drone is ascending, the rotors suck in air from above the drone and send it downwards. This creates a wake where there is significant mixing and turbulence. However, as the drone ascends, it moves away from the turbulent wake and into relatively calm, fresh air above it. During descent, the drone also creates a wake below it but then flies through its own wake. As shown by the velocity vectors in figure 4b, the airflow all around the drone is very turbulent and some of the air from the wake is recirculated by the rotors.

There are some limitations of our simulations given the complexity of the problem. Our model for the rotors does not account for rotation in the air flow under the drone. Rotation caused by the rotors would add extra turbulence and mixing below the drone which may be important when studying the wake structure and characteristics. However, our measurements with the anemometer and estimates from the simulations suggest that the effects of the rotors is small in the region directly underneath the drone where the payload is generally located. Therefore, for our purposes, it is reasonable to neglect rotation from the rotors. Another limitation is the domain size. Our simulations required upwards of 64 million grid cells and ran in parallel on 1000 CPUs. To obtain results in a reasonable amount of time, we used a domain size of 6x6x5 cubic meters with the drone at the center. The boundaries of our domain were over 2 meters away from the drone rotors, however, there may still be some boundary effects on the air flow around the drone. We imposed boundary conditions that would best capture vertical flight in the atmosphere. At the side boundaries, we used an inflow condition with a specified velocity to mimic calm ambient conditions. However, this inflow may cause stronger recirculation in the wake during descent than what is actually experienced during flight.

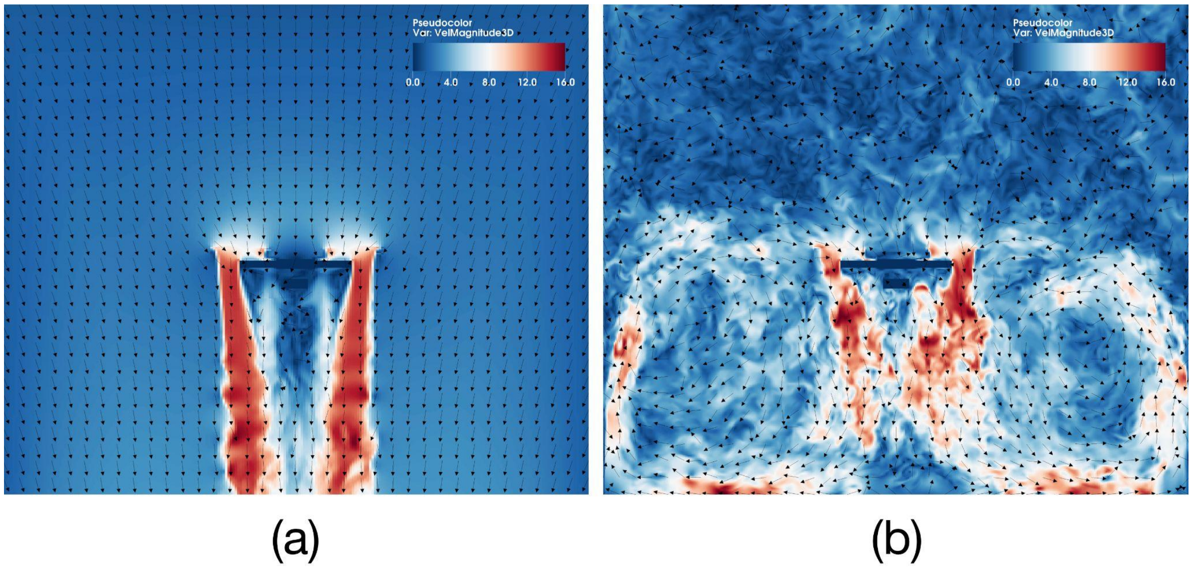


Figure 4: Two-dimensional slices of the 3D simulations air flow from the DJI M600 showing simulated Air flow (velocity contours) and velocity vectors during (a) ascent and (b) descent at t=20 seconds. Colors indicate speed.

Objective 3: Drone measurements compared to balloon borne measurements.

We made measurements simultaneously with identical ozonesondes onboard a drone and a balloon to compare the results from the two platforms. The balloon ascended faster than the drone and landed a few minutes before our arrival, but every effort was made to fly the drone along the same path as the balloon. Figure 5 shows the data collected from the balloon at launch and landing as well as the data from the drone flights. The measurements were made in the late morning or afternoon and the profiles all show uniform ozone concentration. The data from the drone is in good agreement with the balloon. This suggests that drone-based measurements are comparable to balloon-borne observations and that the drone is a suitable platform for air quality measurements. Due to COVID related challenges, we were not able to collect as much data as planned. It would be beneficial to obtain more simultaneous measurements and to collect data at different times of the day when the profiles are not uniform.

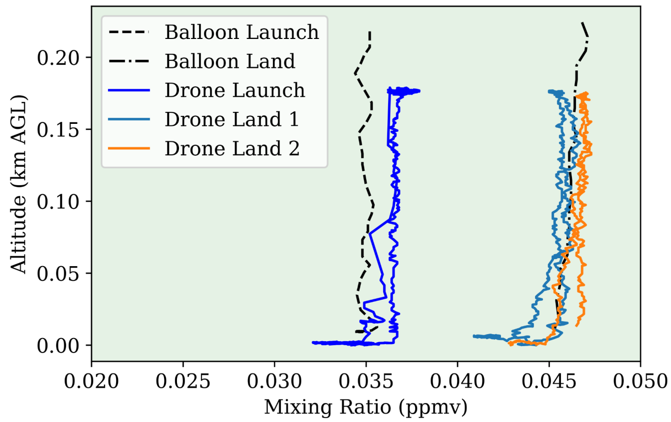


Figure 5: Comparison of ozonesonde measurements from the balloon and drone at balloon launch and shortly after balloon landing. Two drone measurements were made near the balloon landing site.

Objective 4: Determine if drones with lightweight air sensor payloads can reliably measure air pollution vertical profiles in the lower atmosphere.

We collected data from 27 vertical flights using an ozonesonde attached to the DJI M600. Those profiles were collected at various times throughout the day. Selected data from the morning hours is shown in figure 6. In the earlier morning hours, there are notable gradients in the ozone concentration with higher concentrations at higher elevations. By the later morning hours, the ozone concentration is uniform and continues to increase into the afternoon. Figure 7 shows three profiles from the afternoon and three profiles from the evening hours. During the afternoon the profiles remain uniform with concentrations reaching the “moderate” and “unhealthy for sensitive groups” ranges of the Environmental Protection Agency’s (EPA) air quality index. In the evening hours, the profiles become less uniform. The ozone concentration at ground level decreases quickly in the evening but higher concentrations persist at higher elevations. The patterns we observed in our measurements are consistent with observations from previous studies of ozone concentrations along the Wasatch Front[13,14]

A notable feature of the data collected in the morning hours is the large differences in concentration between the profile from ascent and the profile from descent. Similar differences have been observed in other studies using drones to measure air pollution[15]. In each of our measurements, the profile for descent shows higher concentrations than the profile for ascent. Based on our knowledge of the airflow around the drone, we hypothesized that these differences are caused by downward mixing and recirculation that occurs during descent. In our CFD simulations, we transported a passive scalar throughout the domain to represent ozone. We used a time dependent boundary condition to impose a gradient in the simulations and compared the simulation results to our experimental observations.

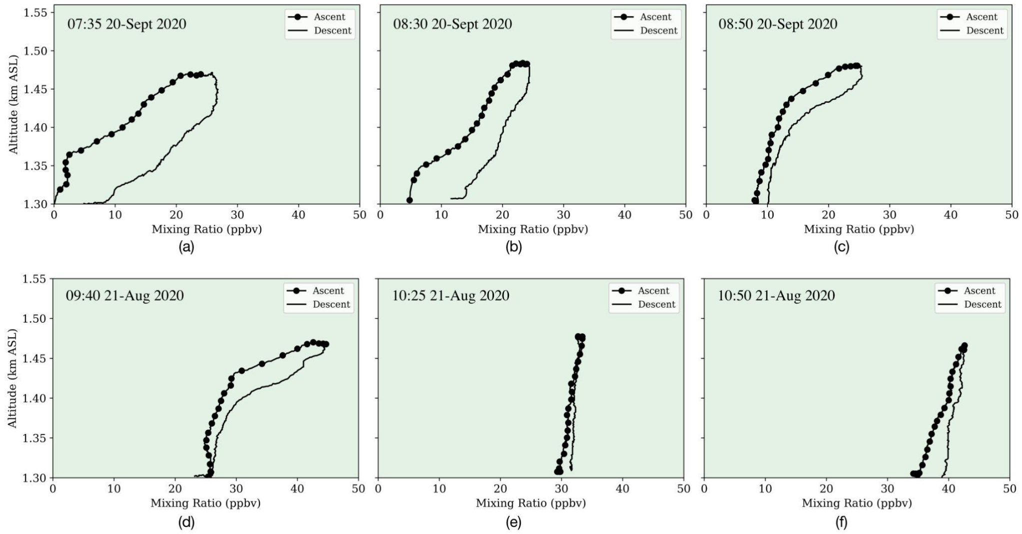


Figure 6: Vertical ozone profiles from August and September 2020 between 7:30 and 10:50 in the morning. Data from ascent is marked with black circles and data from descent is plotted without markers. The background color corresponds to the EPA's air quality index.

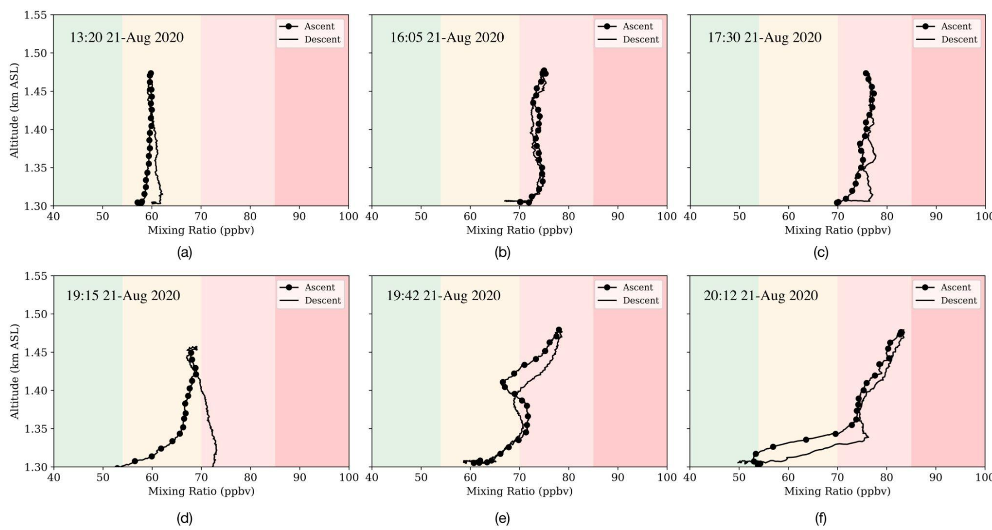
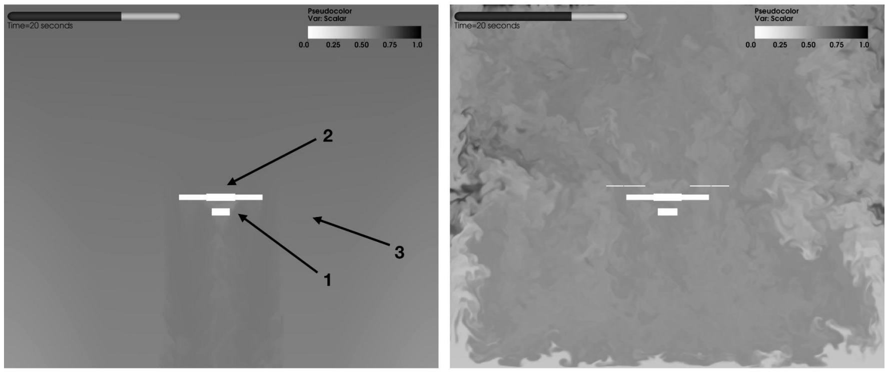


Figure 7: Vertical ozone profiles from August 2020 between 1:20 pm and 8:15 pm. Data from ascent is marked with black circles and data from descent is plotted without markers. The background color corresponds to the EPA's air quality index.

Figure 8 shows 2D slices of the scalar concentration. In figure 8a, three points are marked corresponding to potential intake tube locations: under the drone, above the drone, and outside of the drone rotors. There are clear differences between the ascent and descent. During ascent, because there is little disturbance from the drone rotors away from the drone, a smooth gradient is observed around the drone. During descent, the mixing from the rotors affects the entire domain and air with higher ozone concentrations from above the drone recirculates and persists in the domain for longer periods of time.



(a) (b)

Figure 8: Two-dimensional slices showing the normalized scalar concentration around the drone during (a) ascent and (b) descent. In the figure to the left (a) three potential locations for the intake tube are marked.

To evaluate the profiles from our simulation during ascent and descent, we extracted the nominal scalar concentration value from each of the three locations at each timestep. Figure 9 shows the profiles from ascent and descent at each location plotted with the expected profile based on the boundary conditions set in the input file. The curves for ascent are all clustered together and there are no notable differences between the three locations. In addition, the profiles from the three locations are almost indistinguishable from the expected profile. The curves for descent are also clustered together but are shifted to the right of the expected profile. This indicates that the concentrations calculated by the simulation are all greater than the expected concentration. This trend is in agreement with our experimental results. This shift occurs because of the recirculation caused by the rotors. These results suggest when making measurements with a drone, data should be collected during ascent, especially when there are gradients in the atmosphere. Rather than collecting data during descent, the drone should descend quickly to save battery life. Also, these results suggest that placing the intake tube under the drone will produce accurate measurements and there is no need to extend the intake tube above or to the side of the drone. We attempted measurements with the intake tube extended and found that the extra tubing could absorb or leak ozone if not secured properly and that extra complexity increased the risk of crashing the drone. Our recommendation differs from previous studies which have suggested placing the sensor or intake tube above the drone[11,16,17]. However, our study is the first to perform simulations of ascent and descent. Previous studies have only performed measurements or simulations of hover conditions.

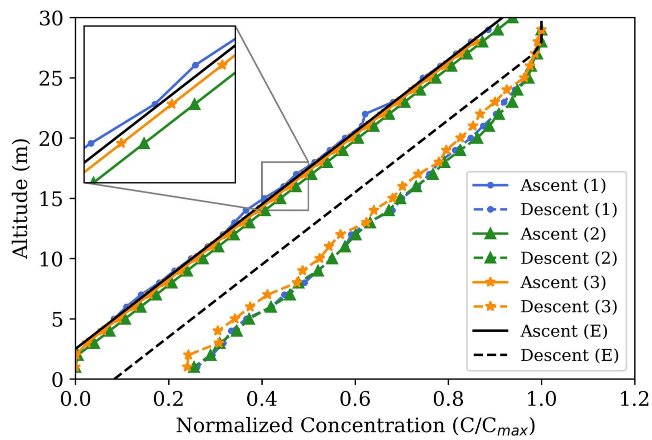


Figure 9: Profiles extracted from the simulations at three potential locations for the intake tube. Location 1 is under the drone, location 2 is above the drone, and location 3 is to the side of the drone past the rotors. The black lines are expected profiles based on the imposed boundary conditions.

Recommendations

- As noted above, we were not able to complete these measurements due to the COVID travel restrictions. These measurements will need to be done in the future.
- Drone-based vertical measurements can be conducted with the payload and intake tube below the center of the drone. Data should be collected during ascent. Any data collected during descent may be biased and should be discarded.
- Additional computational fluid dynamics calculations need to be done with the addition of flight payloads suspended in the rotor wash. Detailed calculations on the air flow and turbulence near the air sample intake tubes needs to be completed.
- Parametric analysis of drone airflow and background ozone and PM2.5 profiles should be conducted computationally in order to devise generalized guidelines.
- Ongoing sets of vertical profiles using a drone-borne air sensor need to be done over an extended period of time and in varying conditions. This is important both for understanding the evolution of our air but also to better understand the use and limitations of drones for air quality measurements.

Data Management

The HARBOR data is stored on the Weber-State University Box storage system. This is not publicly available, but can be provided upon request.

For the simulation results, because of the very large amounts of data generated by three-dimensional CFD calculations, instead of storing the data, it is customary to store the input files used to conduct the simulations along with the version number of the software used at the time of simulation. Those input files can be provided upon request and are stored in a google drive folder.

The simulation software along with the computational model for multirotor drones are open source and available at https://www.github.com/uintah.

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